Development of a Spark Electrode Ignition System for an Explosion Vessel

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***Abstract*—**This paper presents development of an ignition system using spark electrodes for application in a research explosion vessel. A single spark is aimed to be discharged with quantifiable ignition energy. The spark electrode system would enable study of flame propagation, ignitability of fuel-air mixtures and other fundamental characteristics of flames. The principle of the capacitive spark circuit of ASTM is studied to charge an appropriate capacitance connected across the spark gap through a large resistor by a high voltage from the source of power supply until the initiation of spark. Different spark energies could be obtained mainly by varying the value of the capacitance and the supply current. The spark sizes produced are found to be affected by the spark gap, electrode size, input voltage and capacitance value.

***Keywords*—**Ignition, Spark Electrode, Flame

I. Introduction

SINCE the oil crises in the 1970s, improved fuel economy under the constraint of stringent emission standards has become an important goal in combustion system. Fundamental study of flame propagation of fuel-air mixture in an explosion vessel may offer solutions to meet such a requirement, while at the same time improving the fuel efficiency and combustion performance. Many studies were conducted in this field and there is a continuous need for it. In most studies, the parameters of interest would be flame speed, laminar burning velocity and flame stability. Flame study in an explosion vessel requires a suitable spark electrode in order to initiate the flame. A complete understanding of spark ignition is a complex matter, even for a quiescent mixture [1]. From the aspect of thermal theory of electric spark ignition [2], the spark creates a small volume of hot gas instantly after the discharge, followed by a rapid increase in the temperature of the flame kernel. However, further increase in the kernel volume causes the temperature to decreases due to the heat transfer to the relatively cooler ambient unburned gas.

A reliable ignition source is needed to support an explosion vessel rig for the study of flame propagation. Ordinary commercial spark plugs that are used in engines cannot be used for the explosion rig due to various reasons. The geometry of the spark electrode and its holder is critical in avoiding flow disturbance during flame propagation as well as to minimize heat transfer to the electrode body. These may affect accuracy of the parameters involved such as temperature, pressure, and flame speed.

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Previous studies on spark ignition showed that there are variability in results due to the dependence on ignition energy of the electrode construction, materials and discharge circuit design. Quantification of the strength of a short-duration, low-energy capacitive spark ignition source was reported to be difficult for various reasons [3], and therefore a standard for spark energy has not been developed. The ASTM ignition energy test [4] follows the practice started by Lewis and von Elbe [2], which reports only the stored energy rather than measuring the energy discharged into the spark.

The establishment of a self-sustained flame front in the combustible gas mixture is strongly influenced by the discharge mode and the geometry of the plasma volume generated by the spark discharge. The total energy involved plays only a minor role. The spark discharge process can be divided into three main phases: breakdown, arc and glow phases [5]. Spark ignition system of any kind will have a different combination of these three discharge modes, with varying energy content and durations depending on the discharge circuit.

In this paper, the development of a spark electrode system which can generate a single spark for ignition of gaseous fuel mixture in a research explosion vessel is presented. A suitable design and assembly of the spark electrode system is developed in order to ensure reliable operation of the experiment in the customized explosion vessel. Important parameters in the design are studied and these involve the suitable ignition energy, spark gap, ignition duration and also the spark size. In addition, careful consideration is given to the design of electrical power and control circuits for appropriate supply of power in order to generate variable ignition energy for the experiment rig. The system is tested in order to examine its function and performance.

II. Experiment Apparatus and Setup

Shown in Fig. 1 is the high current igniter circuit of the developed ignition system. The system was intended to deliver variable ignition energy of up to one milli-joule (mJ). The entire components of the circuit were determined by experimental simulation of the electrical system to estimate the input and output power of the circuit and the spark duration on an electrical stripboard. The assembly starts with high current igniter that contains a circuit that will create the ignition system. The circuit contains resistor, capacitor, metal–oxide–semiconductor field-effect transistor (MOSFET), diode, and other electrical components to develop a spark at the spark gap between the electrodes. The energy produced at the spark gap must be measurable so that the desired ignition energy can be set for each of the explosion experiments. The switching circuit is a high current igniter circuit. It contains several electrical components that are combined to produce an electrical discharge to the ignition coil. The ignition switch enables the operator to turn the ignition on and release the spark at the spark electrode.

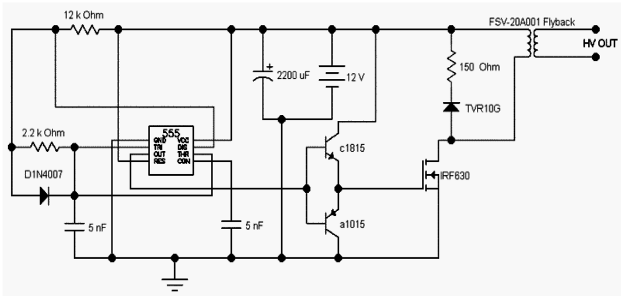

Fig. 1 High current igniter circuit

Through calculation, the current produced into was varied by the input current. With a constant resistance, the current would increase with the voltage input. The circuit output voltage would depend on the current delivered by the timer. However, the voltage output would be lower than the input voltage due to voltage drop across the components. An ignition coil would essentially be an autotransformer with a high ratio of secondary to primary windings. With the autotransformer, the primary and secondary windings would not actually be separated as they shared a few of the windings. The actual spark is generated when the breaker contacts open. For an ideal inductor, the current and voltage are related by:

$$V = L\,dI \tag{1}$$

where V is the voltage (V), L is the inductance (in Henrys) and dI is the rate of change of the current (A). Thus, considering that L is constant for the inductor, an abrupt change in current would cause a very large voltage to be produced, and consequently a very short and high voltage spike. The change in current is on the primary side. However, because the primary and secondary coils have a large mutual inductance, it would spike in the order of 100 or more volts on the primary coil, and more than 10000 volts on the secondary coil. The Paschen's Law was used to determine the output voltage in this work.

The designed spark electrode contains three main parts which are the center electrode, ground electrode and insulator. The main purpose of the design specification is to suite with the size of the explosion vessel. The internal diameter of the explosion vessel is 350 mm. A common commercial spark plug contains terminal electrode, ground electrode and insulator. The terminal and ground electrodes are usually made from high nickel alloy and the insulator is made from aluminum oxide (alumina) ceramic. Nickel is usually chosen as it is a versatile element, which will alloy with most metals. Table I shows the insulator requirement for the spark electrode based on common spark plug design.

TABLE I
INSULATOR DESIGN REQUIREMENTS [6]

Material Class	Ceramics
Process Class	Primary, Discrete
Shape Class	Hollow-stepped
Minimum Section	1.2 mm

Shown in Fig. 2 is the initial design of the spark electrode. It is designed long so that the spark gas can be positioned at the center point of the explosion vessel, with flexibility of shifting the linear position if there is a need for such a requirement. The diameter of the electrode is 2 mm. The electrode is insulated with ceramic, of which the diameter is 7.5 mm. The side electrode is a short, thick wire made of nickel alloy that is connected to the insulator and extends toward the center electrode. The tips of the side and center electrodes are adjustable so that we can study the effect of the spark gap also that creates the gap for the spark to jump across. Shown in Table II is summary of the specification of the electrode size and material. The electrode was test using a digital multi function tester to check for any leakage through the insulator and whether the design meets the basic standard to deliver the spark safely.

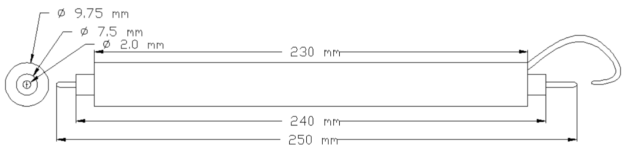

Fig. 2 Initial design of spark electrode

TABLE II
SUMMARY OF ELECTRODE DESIGN

	Indication	Material	Length (mm)	Outer diameter (mm)
Center Electrode	Inside Rod	Nickel	250	2.00
Ground Electrode	Outside Rod	Nickel	230	9.75
Insulator	Middle Rod	Ceramic	240	7.50

Fig. 3 shows full assembly of the ignition system, which is synchronized with the high-speed digital camera and trigger system. The high-speed camera system is part of the setup for the explosion study, in which images of flame propagation are captured at high framing rate (typically 1000 frame per second). The setting shown in Fig. 3 contains the DC power supply system, ignition system, spark electrode, high-speed digital camera, timer, signal converter, trigger switch, signal converter, and a few other minor components. The main part is the ignition system, which is shown in Fig. 3 as bounded by a dashed line box. The main function of the ignition system is to prepare and temporarily store the potential electrical energy for the spark electrode. The signal converter is used to convert the signal from power supply and in the same time transfer it to pulse receiver in ignition system and high speed camera so that both component will function simultaneously which is to produce enough voltage to develop the spark and also react the camera to capture the spark's image. Synchronization of the high-speed camera system with the spark ignition system is necessary because the spark duration is very short and the duration for the camera to operate is also limited, and thus manual starting of the two systems is impossible.

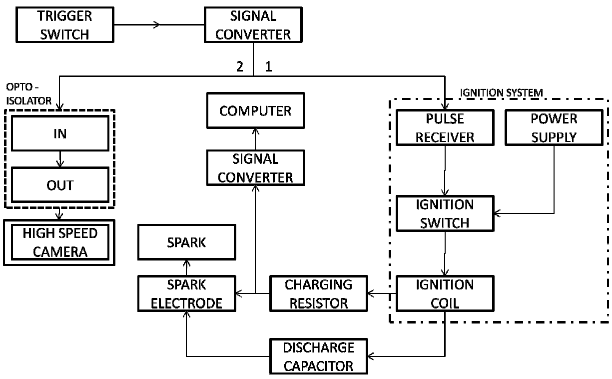

Fig. 3 Schematic of control circuit for ignition system and synchronization with high speed camera

The spark energy, E, was calculated by:

$$E = ½\, CV^2 \tag{2}$$

where C is the energy storage capacitance, which is the sum of the capacitance of the electrode gap and the stray capacitance. V is the spark voltage at the moment of discharge. C and V have the usual standard units of F (Farad) and V (Volt). The capacitor value was manipulated to obtain a different energy value that produced at the spark gap. Four capacitors of different rating were used in the circuit to vary the spark energy. However the peak voltage that was produced from the flyback transformer was difficult to measure, and therefore the Paschen's Law theory was employed to estimate the value of the peak voltage. Paschen described the air breakdown voltage as:

$$V = \frac{a(pd)}{\ln(pd) + b} \tag{3}$$

where V is the breakdown voltage in volts, p is the pressure in atmospheres in bar, d is the spark gap distance in meters. The constant a and b depend upon the composition of the gas. For air at standard atmospheric pressure, a = 43.6 x 10^6 V/(atm.m) and b = 12.8. At first, the gap for the electrode would be set to 0.5 mm and would be increased until no spark could occur. The current from the power supply shall then be varied from 3.5 A to 4.5 A with a constant voltage of 12 V. Once there is no spark observed, for example at a gap distance of 3 mm, the value is added to the Paschen's Law equation to estimate the value of spark discharge based on the supply power. Then, the voltage value will be added to Eqn. (1) together with the discharge capacitor value to estimate the energy that is produced by the theoretical calculation.

III. Results and Discussions

Based on several calculations and electrical simulations from Fig. 2, the complete ignition circuit was developed and is shown in Fig. 4.

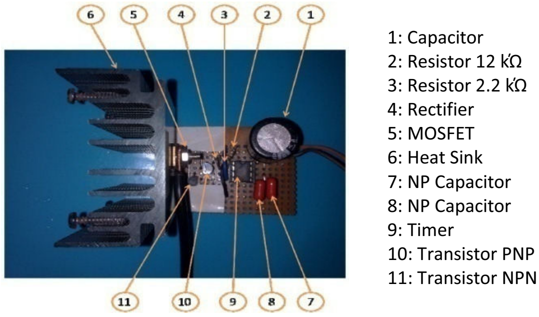

Fig. 4 Ignition circuit

A. Output Voltage

In order to estimate the high peak voltage, the maximum spark gap size that could result in the spark was tested. For an example, with the box blue capacitor which had a 6.8 pf capacitance value and using a 12 V and 3.5 A input, the maximum gap that can result in the spark was 1.5 mm. Based on the Paschen's Law equation, the output voltage was calculated to be 10.50 kV. Fig. 5 shows the variation of the largest gap for spark to occur with the input current for different capacitance (1.0, 4.72 and 6.8 pF). As a result, the output voltage was determined using the Paschen's Law or Eqn. (3). It is shown in Fig. 6 that generally the bigger the input current, the higher would be the maximum air gap. A decrease in the capacitance is shown to increase the maximum air gap.

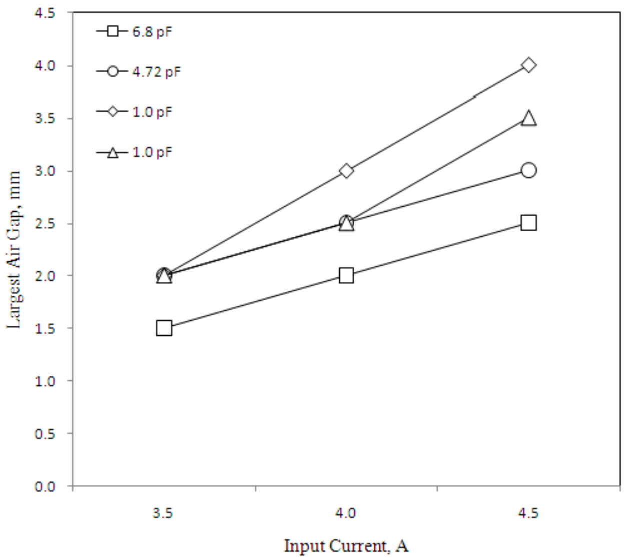

Fig. 5 Variation of maximum air gap with input current

B. Ignition Energy

Ignition energy is the amount of energy that an electric spark discharge has to deliver for ignition of a given fuel-air mixture at given conditions or at atmosphere. In the present study, the ignition energy is actually the energy stored in the capacitor to create the electrical discharge. The stored energy was varied by using different combinations of capacitors and different charging voltages which were varied from 1 kV to 24 kV by the Paschen's Law calculation. The voltage was predicted as the capacitor was charged, and the spark was triggered when the desired charging voltage was reached and stabilized. Fig. 6 shows the variation of spark energy with the output voltage for different capacitance values.

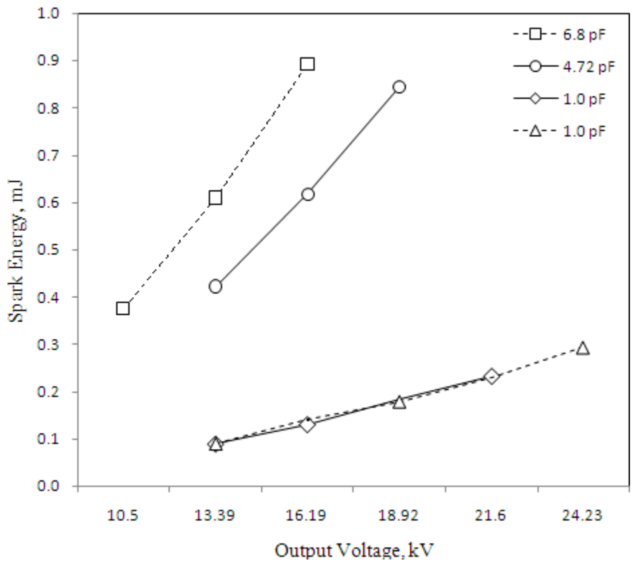

Fig. 6 Variation of spark energy based on output voltage

The images of the spark kernel were captured using Phantom V9 high speed camera. The image resolution of the camera was set to 96 x 48 pixels and the capturing image was set to catch 80,000 frames per second (fps). In other word, images were captured at an interval of 12.5 µs. The spark size was defines as the vertical height of the spark as measured from the images. The effect of varying spark energy on spark size is shown in Fig. 7 for different spark gaps. The coil primary current was varied to obtain spark energy of between 0.0897 mJ and 0.8912 mJ, which ranged between minimum levels to a certain maximum level that can ensure establishment of sparks. The size of the spark kernel is shown in Fig. 7 to be of between 1.5 mm and 7.5 mm.

In Fig. 8, the effect of capacitance value and the spark gap on the spark size (height) can be seen much clearly. An increase in the capacitance value will increase the ignition energy. It is also shown in Fig. 8 that an increase in the spark gap will generally increase the spark size. Obviously, the biggest spark size that was obtained from the experiments was almost 8 mm in size, which was being resulted by the use of a 4.5 A input current with a 2.0 mm gap (largest). Despite the trend, there are some results that are found to be contradicting. This can be seen in Fig. 8 for the 1.0 mm gap, in which for a 0.1306 mJ spark energy, the spark size was shown to be larger than that for the 0.1790 mJ spark energy. The reason for this irregularity might be due to the effect of electrode temperature and the malfunctioning transformer caused by frequent usage within a short period of time. From the experiments, it can be generalized that spark size kernel depends on the spark energy and the spark gap.

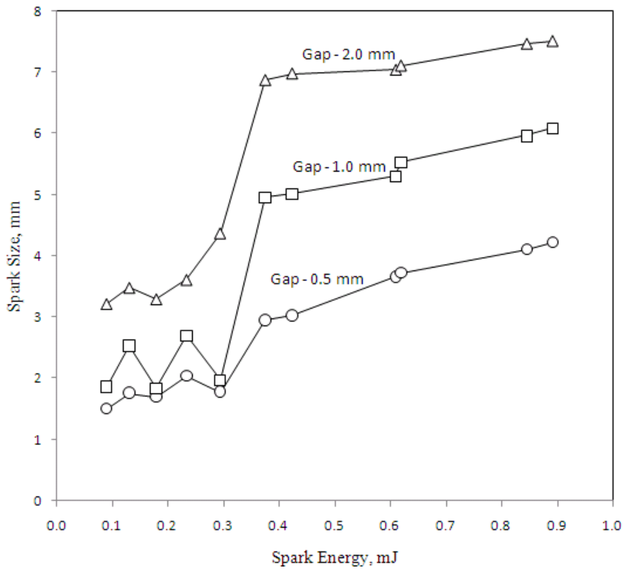

Fig. 7 Effect of different spark ignition energy and spark gap on spark size

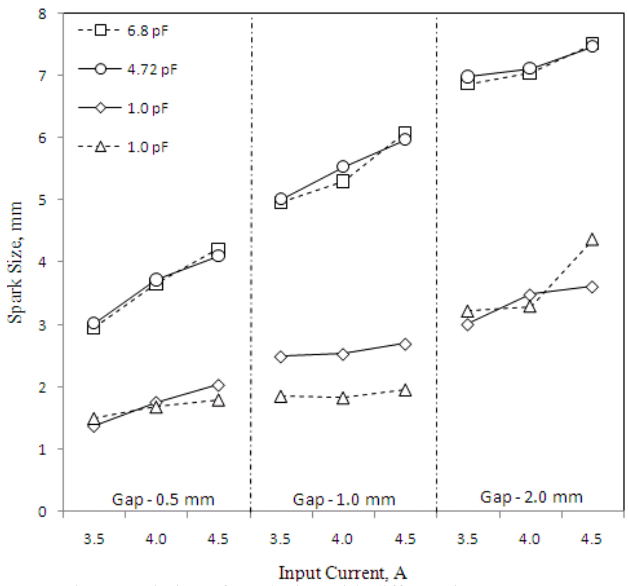

Fig. 8 Variation of spark size with different input current

C. Variation of Spark Kernel Growth

The high-speed digital camera recorded history of the shape and size of the developing flame kernel. A variation in the temporal distribution of the spark energy would influence the minimum ignition energy and the rate of kernel growth [8].

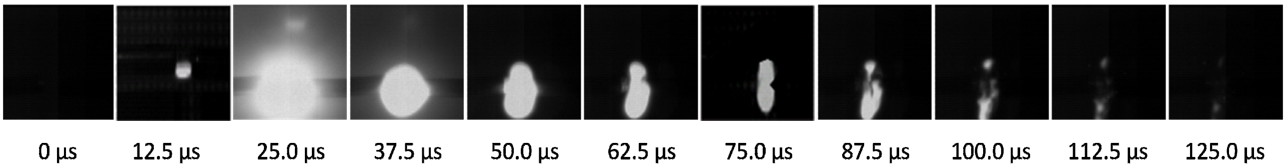

Fig. 9 Sequence of natural light images of electric spark in air at ambient condition at 12.5 µs interval

The experimental part of the present study involved recording of temporal development of the spark kernels. Fig. 9 shows sequence of natural light images of electric spark in air at ambient condition from the start of ignition until it diminished. The whole spark duration was observed for a duration of 125 µs. A shutter speed of 12.5 µs and framing rate of 80,000 fps were set with a spark gap of 2.0 mm for the experiment in this figure. The frame at 25 µs shows a very bright spark which suggests the high temperature kernel and the ellipsoidal trace of a weak shock wave generated by the breakdown event as described by Lim et al. [10]. Shown in Fig. 10 is variation of the spark size with time from the start of ignition for the images in Fig. 10. Kernel radii of equivalent sparks in atmosphere exhibit a difference as early as 12.5 µs after breakdown. The initially rapid growth of the kernel during the spark discharge was adequately predicted with a mass entrainment term that is a function of the electrical power input as suggested by Lim et al. [10]. Upon reaching the peak size, the spark slowly decayed in size until at 125 µs. The variations of spark development were determined to obtain a suitable ignition period for combustion or explosion system to make sure the combustion is perfectly conducted.

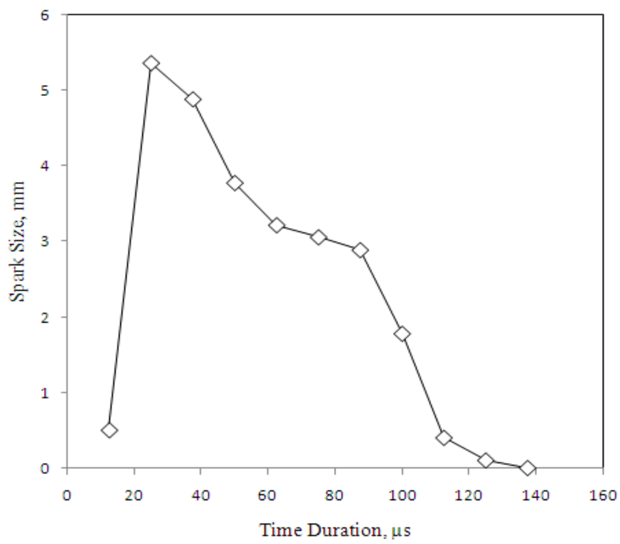

Fig. 10 Variation of spark width with time from the static of ignition for static conditions

D. Fabricated Electrode

The design of the spark electrode was finalized with high nickel alloy specified for the ground and center electrodes and using ceramic for the insulator. The complete assembly of all the electrode components components can be seen in Fig. 11. The insulation diameter is 8.5 mm and the outer casing of the electrode is 9.75 mm in diameter. The overall length of the electrode holder is 250 mm. However, due to difficulty in getting a high nickel alloy and difficulty in cutting the metal, both center and ground electrode materials were changed to stainless steel. The explosion in the vessel during experiment would last for only about 50 to 100 ms, which is short, and therefore usage of stainless steel would be acceptable even though the explosion flame temperature would be high (up to 2000 K).

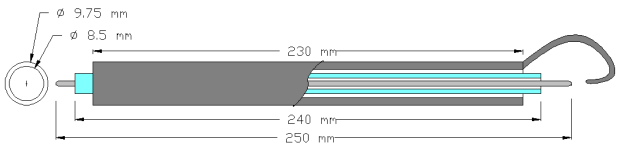

Fig. 11 Complete fabricated electrode

In order to determine whether the insulator can function as desired, a Digital Multi Function Tester Model 6011 unit was used to determine the leakage at the insulator (Meggar test). Since the Ohm's Law applies, the leaked current was divided by an applied high voltage to obtain the insulation resistance (MΩ). The insulation resistance for the spark electrode was measured to be 19.01 MΩ. Based on the insulation test, the amount of leaked current was calculated to be very small; i.e. 52.6 µA. This amount of leakage current would be relative low and safe as compared to the 3.5 A minimum current supplied. The percentage of leakage current was calculated to be just 1.5 % and was thus negligible.

E. System Functionality

In order to determine the functionality of the system in providing the ignition spark, the system was tested with a bunsen burner, which was supplied with butane fuel gas. The experiment was performed in an open lab area, which was subjected to atmospheric condition. It was found that with a 6.8 pF capacitor, all the igntion energy and spark gap could successfully igntite the gas. The same observation was found for a 4.7 pF capacitor, owing to the high ignition energy it produced. However, for the 1.0 pF capacitors, which could produced a maximum spark energy of 0.294 mJ, the usage of a 0.5 mm gap failed ignite the gas. This can be explained due to the effect of spark size that produced by such a configuration of spark system. In Fig. 12, the sequence of images of the spark of the butane gas is shown. The images were captured by using the high speed camera with natural light. The image

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framing rate was 1200 fps, which gave an interval of 0.83 ms between each successive frame. The time taken for the butane fuel gas to fully ignite was about 3 ms as observed from the figure.

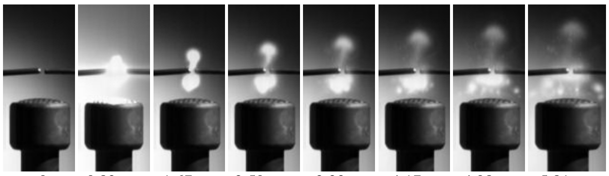

Fig. 12 Sequence of natural light imaging for up to 5.81 ms after ignition of spark

IV. Conclusion

The objective of the present work to develop a spark electrode for an explosion vessel has been met. From this work, the following conclusions can be drawn:

1. The spark size produced was affected by the spark gap, electrode size, input voltage and capacitance value.
2. Kernel of spark in atmospheric air was exhibited as early as 12.5 µs after the breakdown. This suggests that kernel growth by chemical energy release occurs very early in the process.
3. The most effective spark gap for ignition would be slightly greater than the quenching distance where it refers to the minimum distance between the electrodes which allows optimal ignition, with a minimal energy loss to the electrodes. Larger spark size may affect the equipment or system.

Thus, the system was confirmed suitable to be used in providing the ignition energy for gaseous fuel in explosion study in the vessel.

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